All Things Neutrinos

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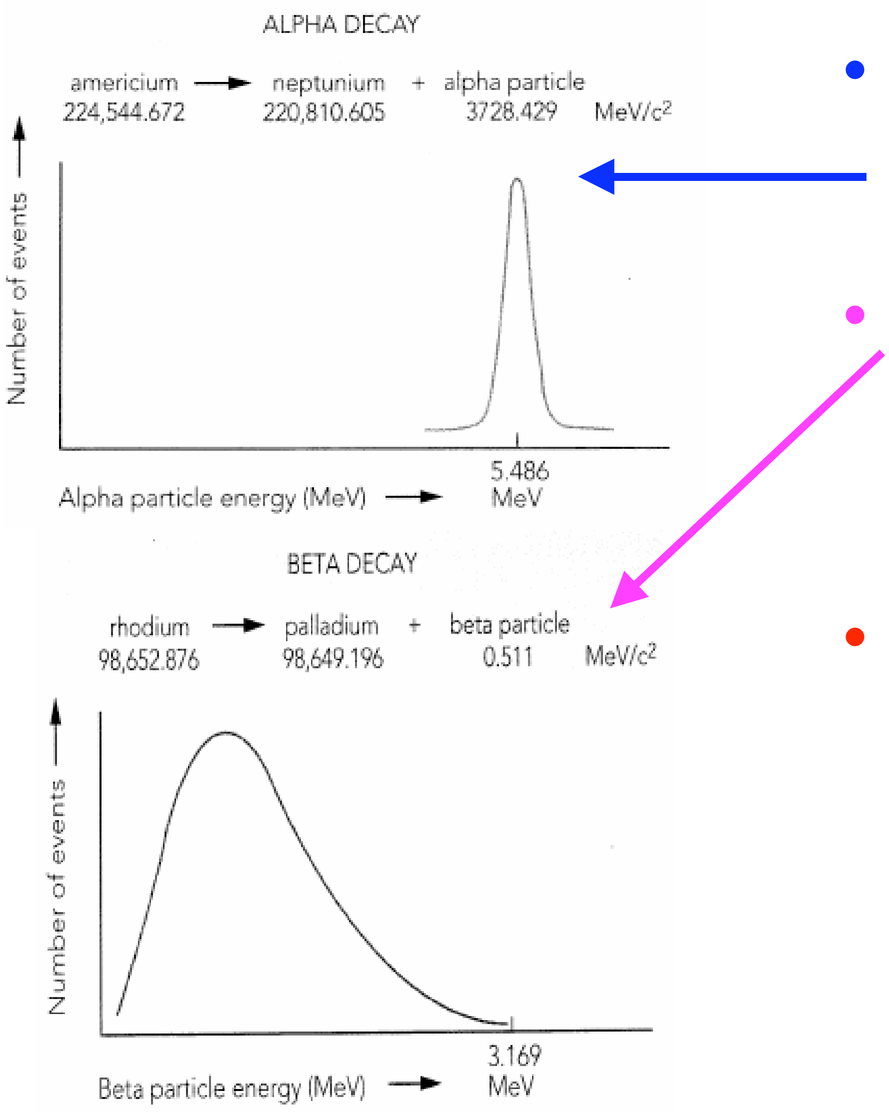
Outline

- Neutrinos & The Standard Model of Physics
- Oscillations
- Sources of Neutrinos
- Detecting Neutrinos
  - Interactions with matter
  - Detection techniques
  - Examples of detectors
- Oscillation Results
- Sampling of Neutrino Theories

Cool Neutrino Facts

- Human body = 20 mg of Potassium 40. Humans emit 340 million neutrinos per day!
- 100,000 billion pass through your body each second from the sun
  - Your body will stop ~1 neutrino which passes through it in a lifetime!

Why Neutrinos?



- 2 body alpha decay, E of decay products always the same
- 1913 - 1930 : beta decay = continuous spectrum of E
  - E not conserved?
  - P not conserved?
- "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." (Pauli, 1930)

Two Body Decay Kinematics

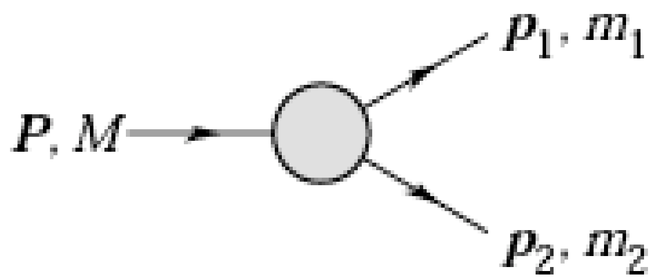


Figure 38.1: Definitions of variables for two-body decays.

38.4.2. ***Two-body decays:***

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

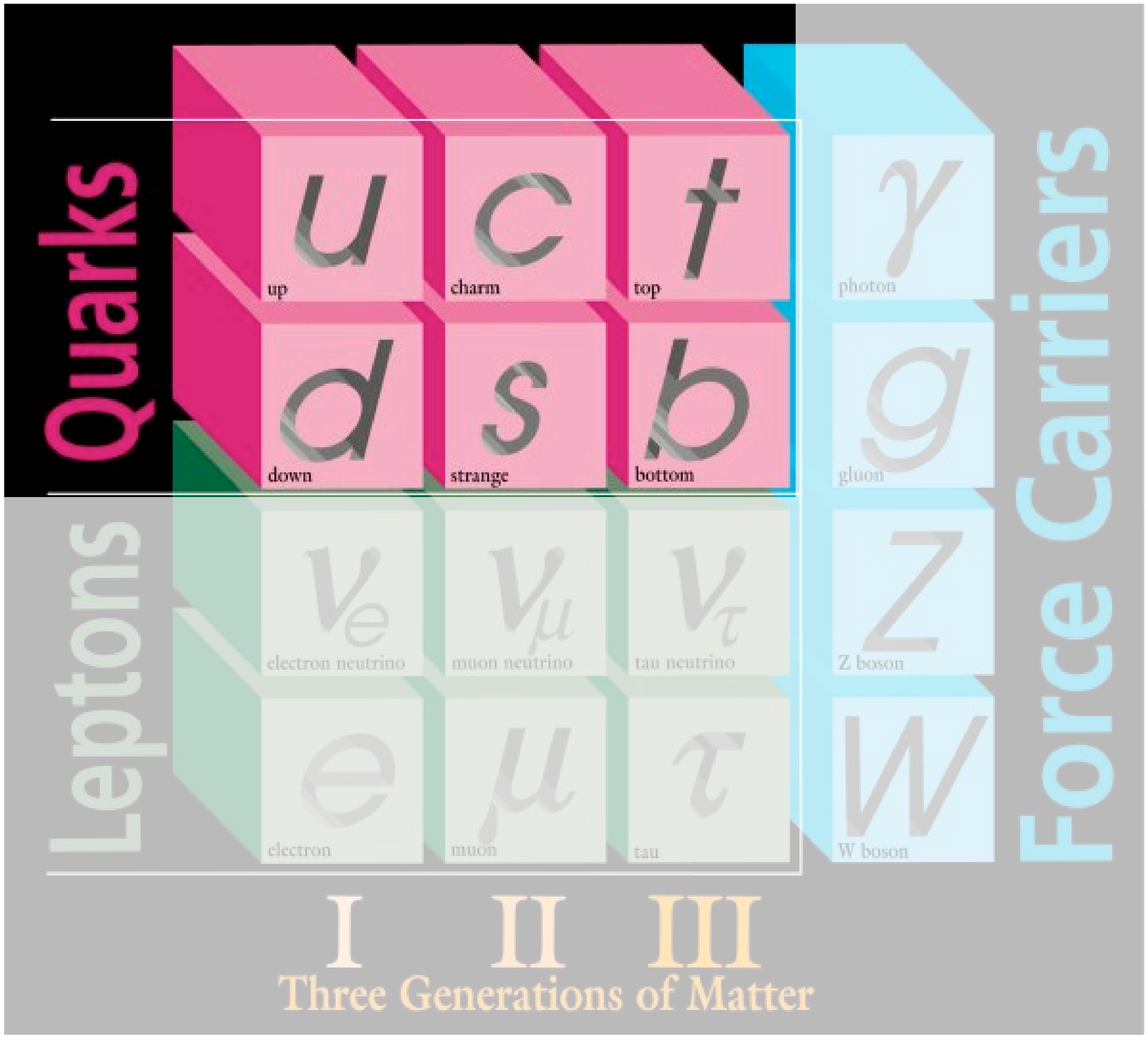
$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M} \;, \tag{38.15}$$

$$|p_1| = |p_2|$$

Standard Model of Physics

+2/3

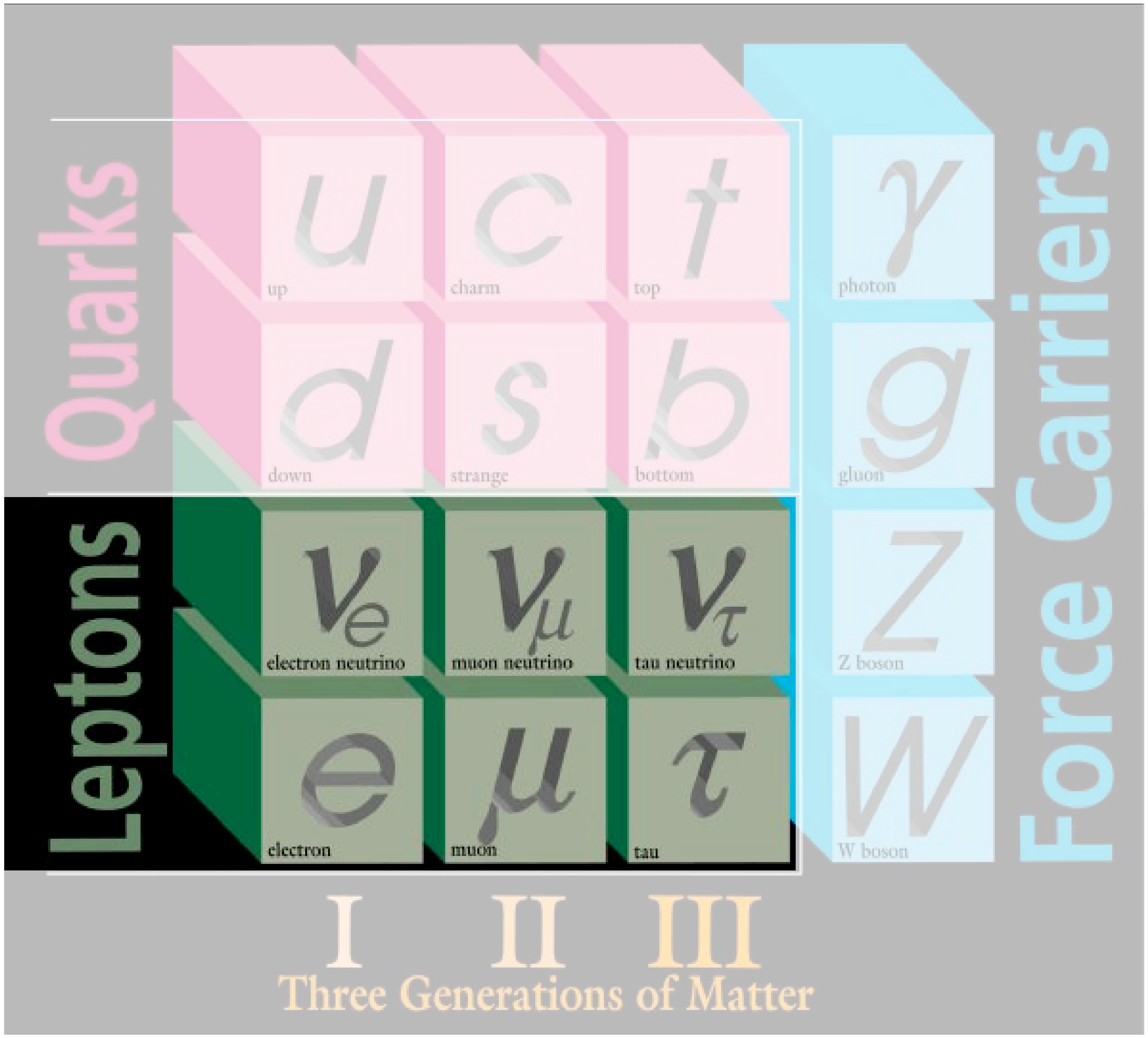
-1/3



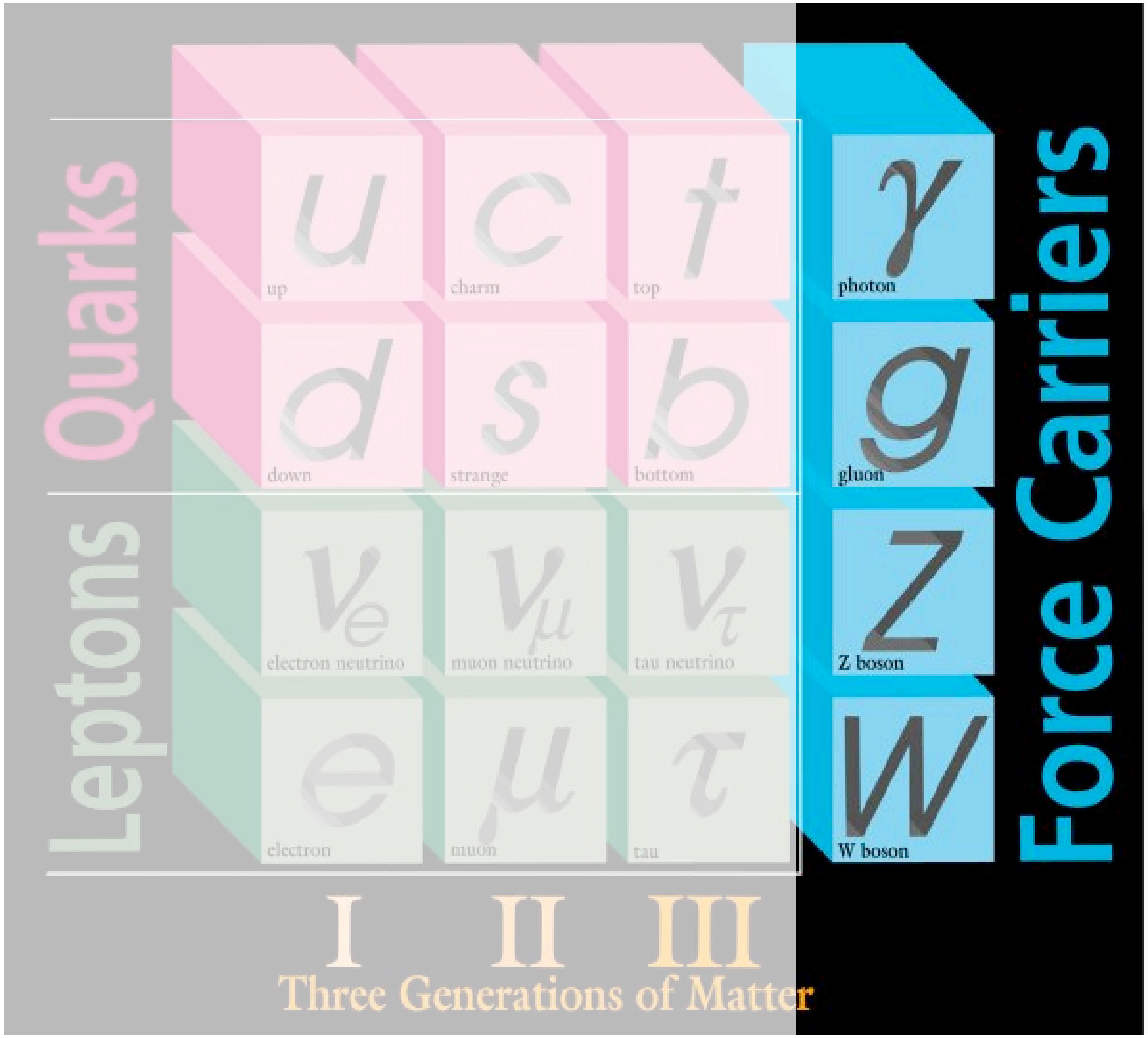
Standard Model of Physics

0

−1



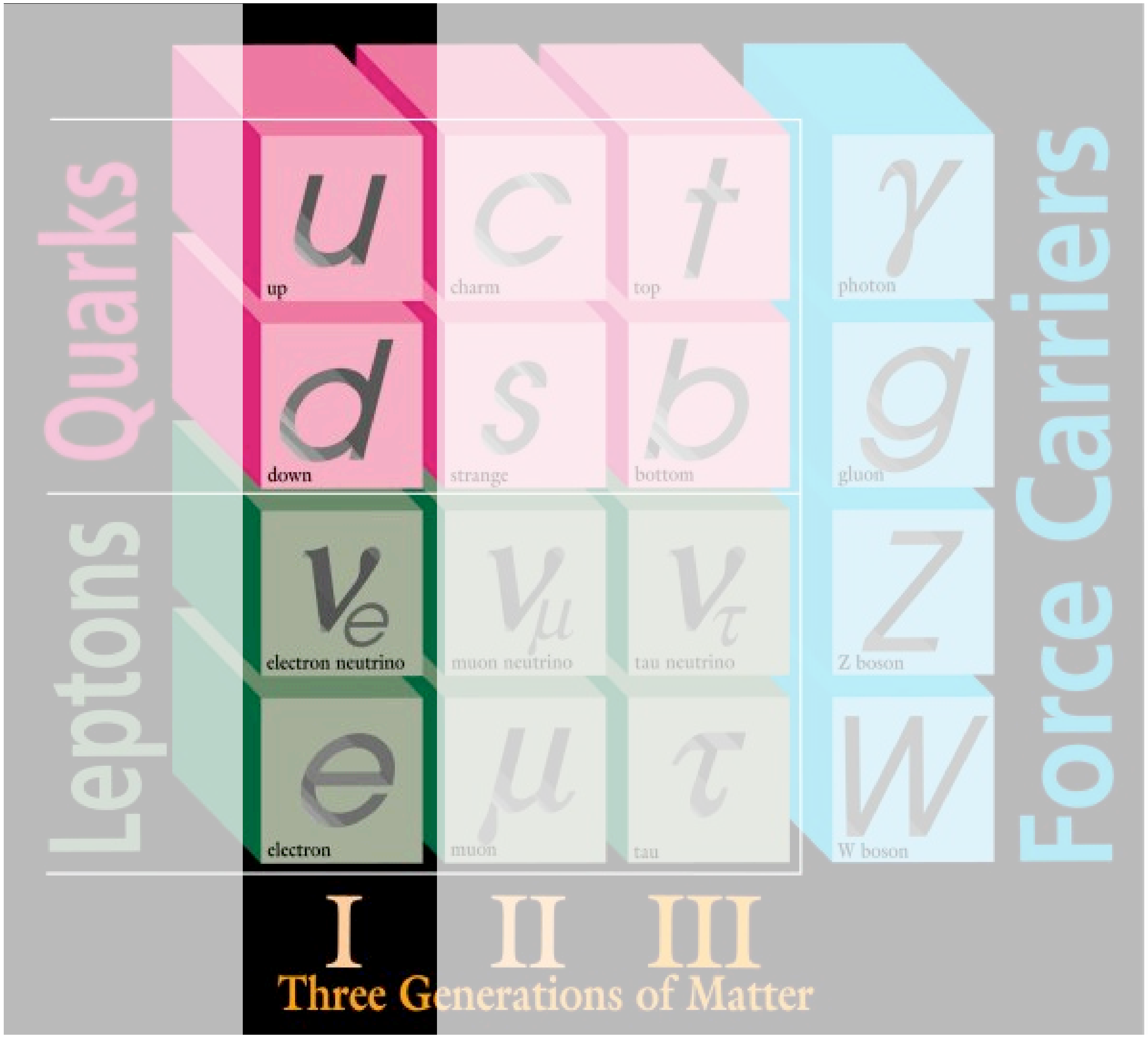
Standard Model of Physics



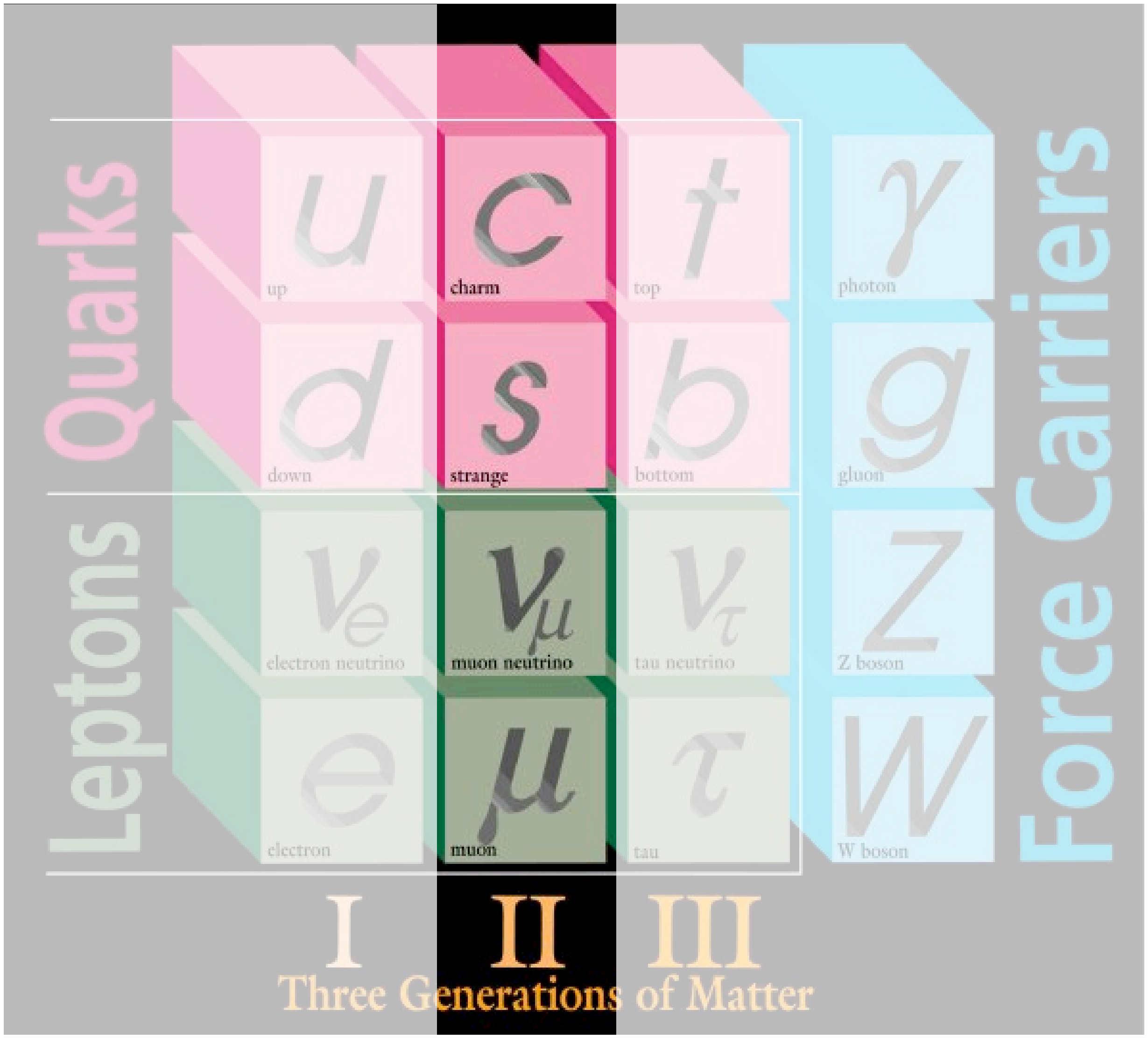
0

±1

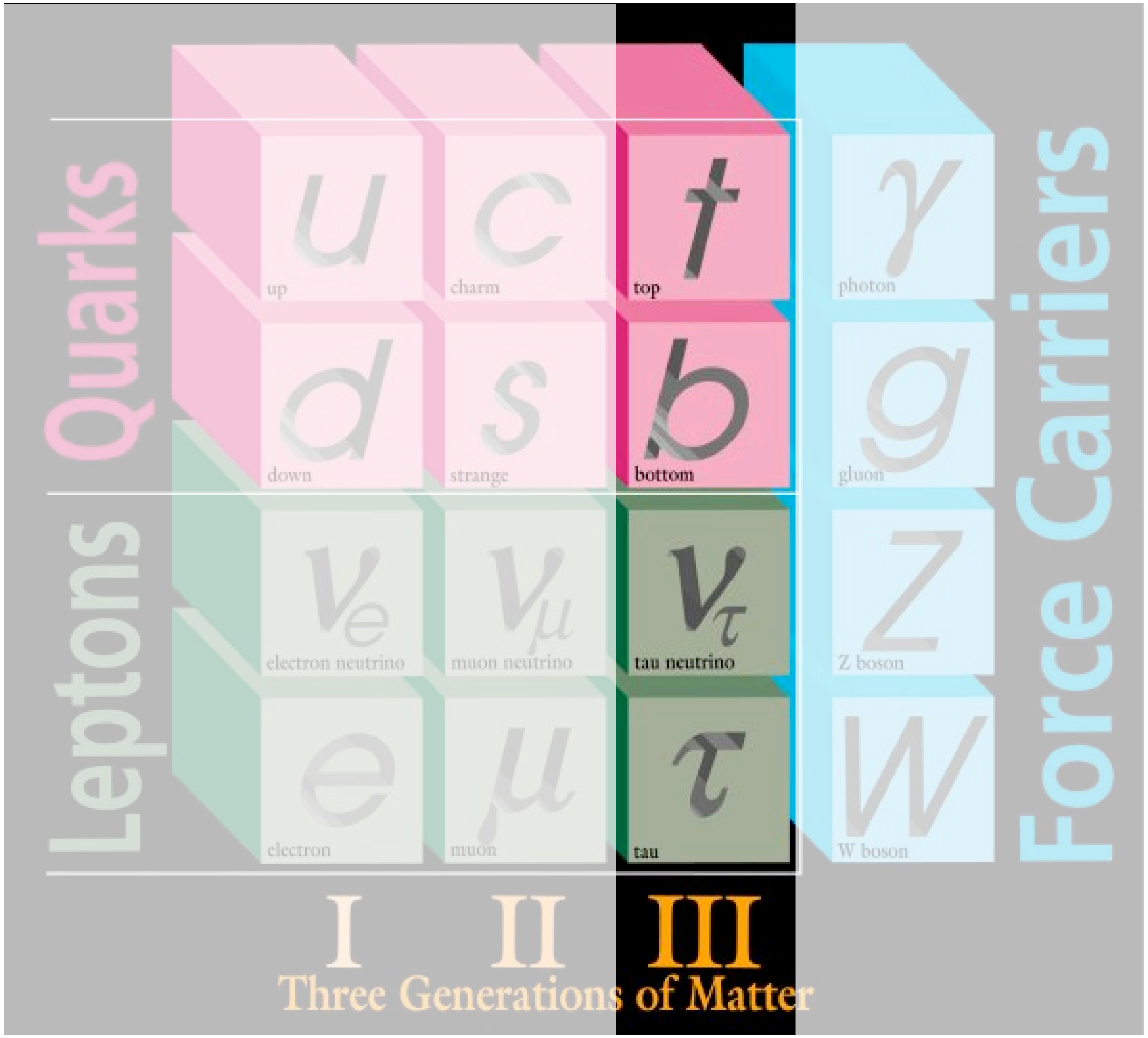
Standard Model of Physics



Standard Model of Physics



Standard Model of Physics



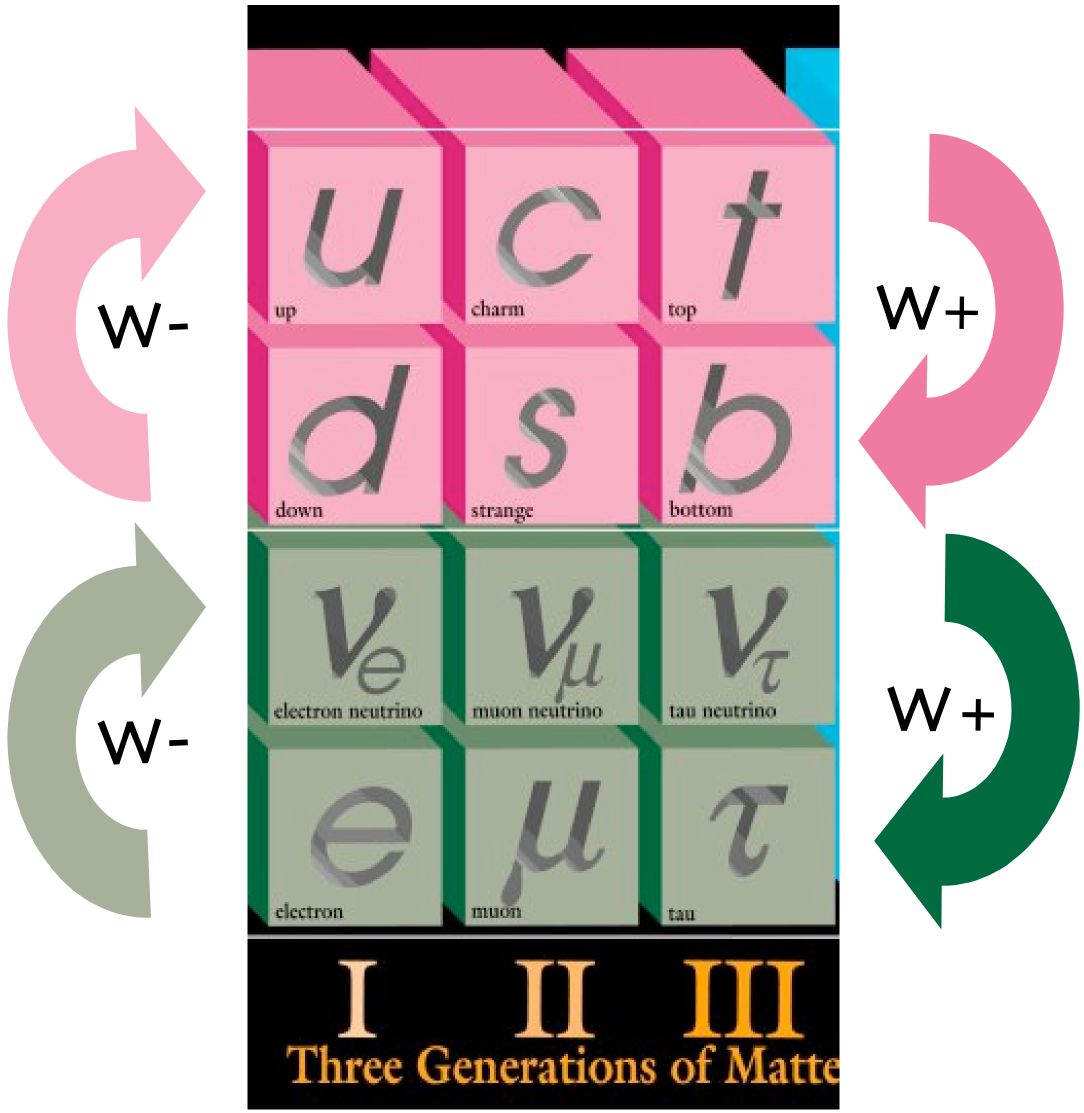
Standard Model of Physics

- Also have 12 anti-particles (same mass & lifetime, opposite charge)
- Gauge particles mediate or transmit forces between particles
- Forces that create particles also dictate which interactions particles can participate in
- E-M : particles with electric charge
  - Quarks, leptons
- Strong : binds quarks together
  - Quarks

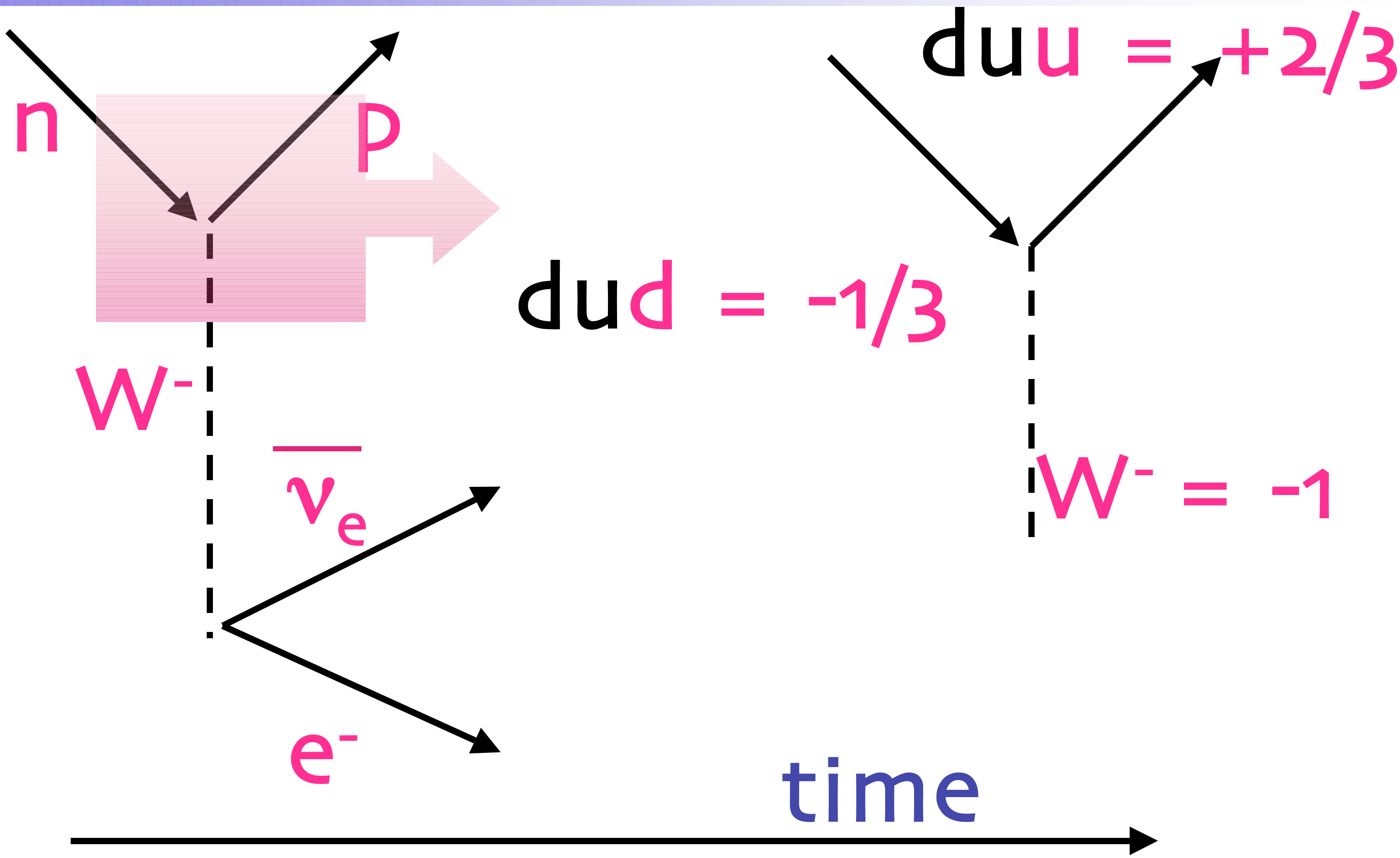
Standard Model of Physics

- Weak : force of transmutation!
  - changes flavor of quarks, leptons *within a family*
  - Only force that acts on neutrinos
  - Neutral current = no exchange of electric charge (Z)
  - Charged current = exchange electric charge (W^+, W^-)

Standard Model of Physics



Ex : Beta Decay



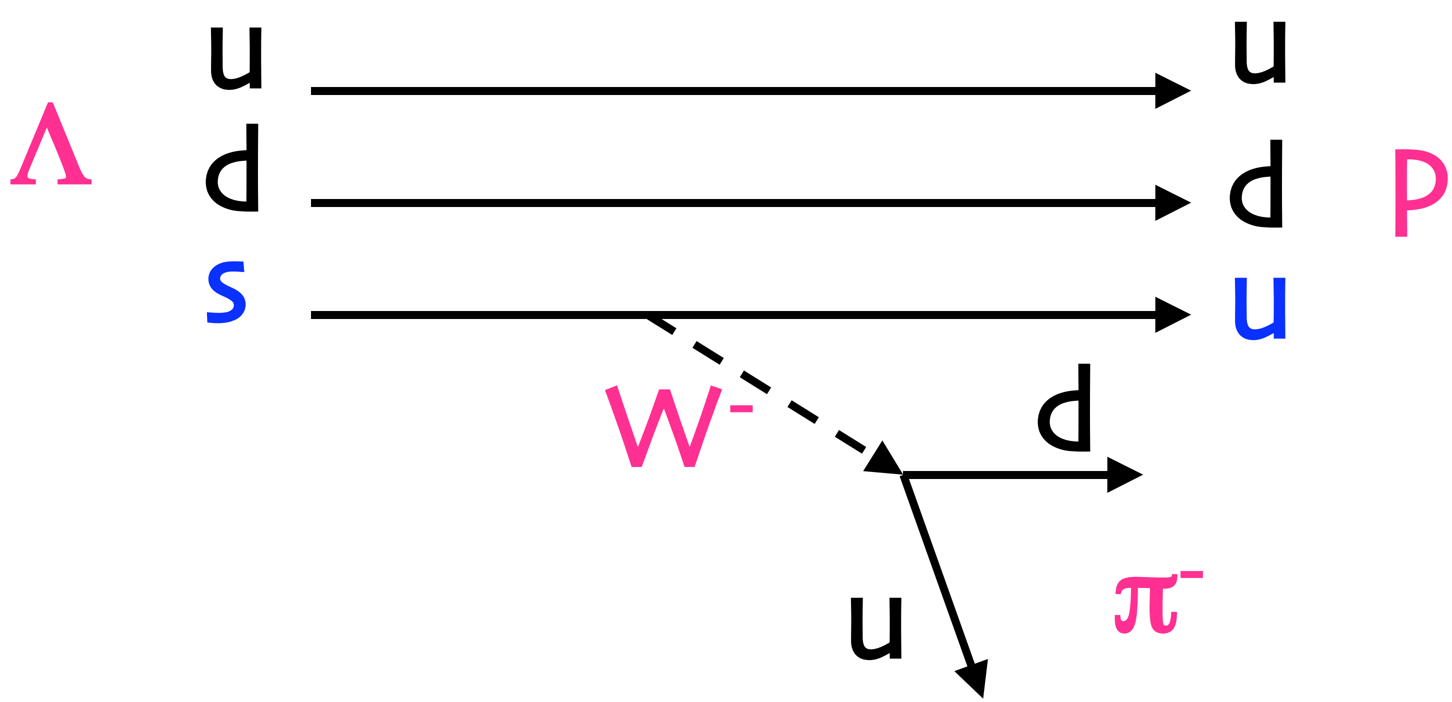
Neutrinos in the Standard Model

- Neutrinos are massless
- Neutrinos only interact via the Weak force
- Neutrinos are left-handed
  - anti-neutrinos are right-handed
- Neutrinos are electrically neutral
- Neutrinos have three flavors
  - Electron, muon, tau

Oscillation Physics

Quark Mixing

- Problem! If Weak force only acts inside of a family - how do you explain lambda decay?



Quark Mixing

- Solution : quark generations are rotated for the purposes of weak interactions
- Instead of the Weak force coupling to

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

- It couples to

$$\begin{pmatrix} u \\ d' \end{pmatrix}$$

Quark Mixing

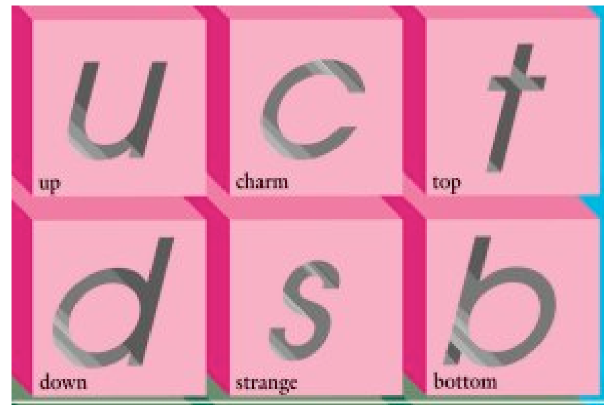
- Where d′ is a linear combination of the d, s, b quarks
  - mixing that results from mis-alignment of weak and mass states is a natural outcome of the symmetry-breaking mechanism by which particles acquire mass

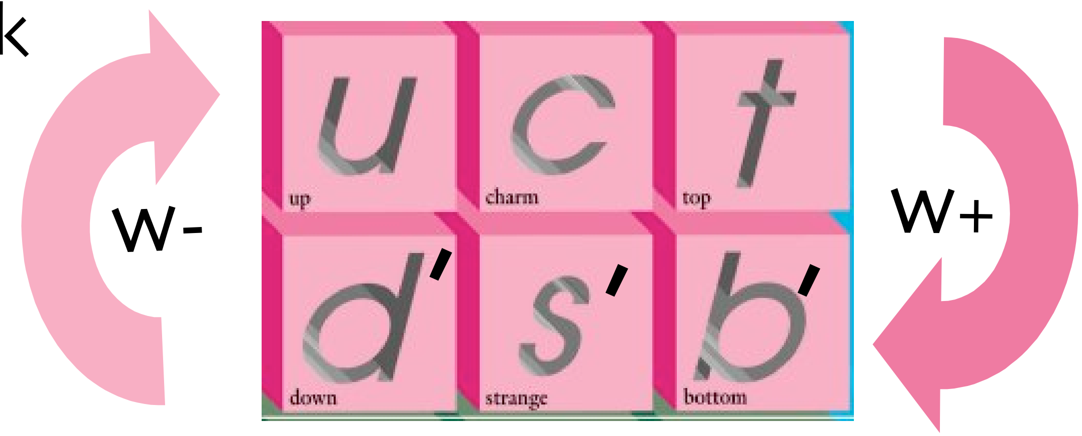
Weak state Mass state

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & & \\ V_{td} & & \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Quark Mixing

- States which participate in Strong interactions are mass states
- States which participate in Weak interactions are mixtures of mass states





Lepton Mixing

- Why doesn't same thing happen to leptons?
  - SM = mass and weak states are identical because the neutrino has no mass!
- If neutrinos are massive have analogous situation for neutrino-lepton pairs

Neutrino Oscillations

Weak state Mass state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Neutrino Oscillations

Weak state $\qquad\qquad\qquad\qquad$ Mass state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(0)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Neutrino Oscillations

Weak state Mass state

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(t)> \; = -\sin\theta \, \underbrace{|\nu_1>}_{e^{-iE_1t}} + \cos\theta \, \underbrace{|\nu_2>}_{e^{-iE_2t}}$$

Neutrino Oscillations

$$P_{osc} = |\langle \nu_e | \nu_\mu(t) \rangle|^2$$

$$P_{osc} = \sin^2 2\theta \, \sin^2 \left(\frac{1.27 \, \Delta m^2 \, L}{E} \right)$$

Neutrino Oscillations

Δm^2 is the mass squared difference between the two neutrino states

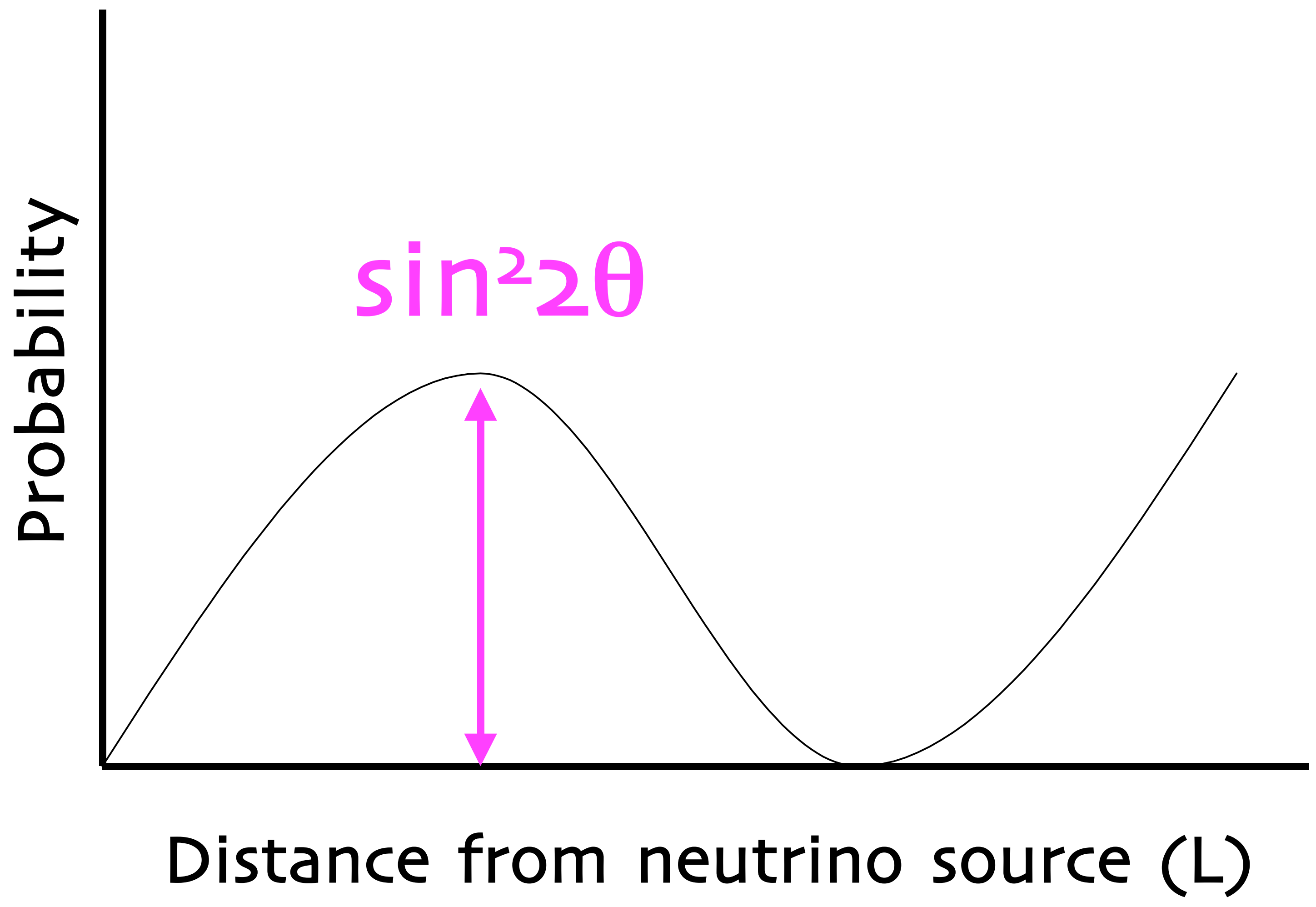
Distance from point of creation of neutrino beam to detection point

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$

θ Is the mixing angle

E is the energy of the neutrino beam

Neutrino Oscillations

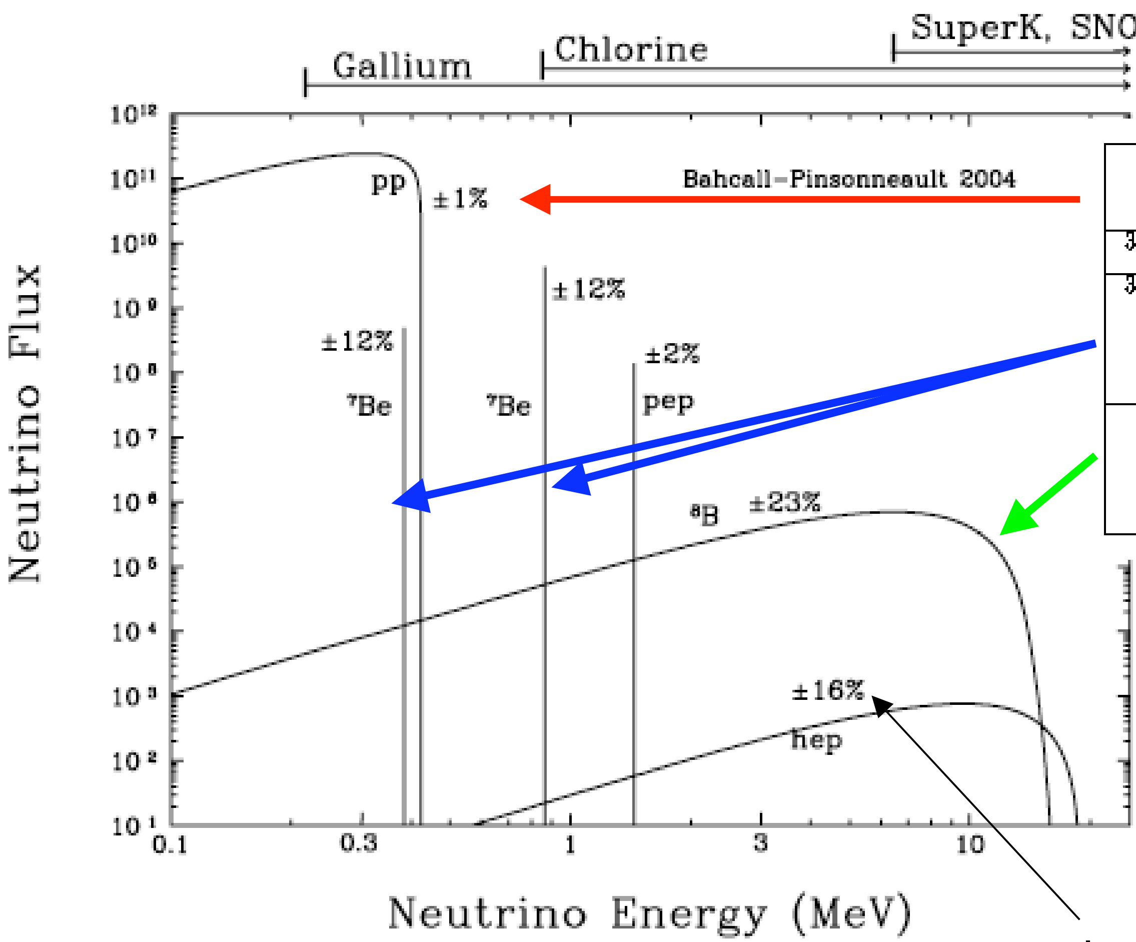


Sources of Neutrinos

Neutrino Sources

- Solar : ~ 0.1 - 15 MeV (10^6 eV)
  - from fusion inside of stars
  - 85% from $p+p \rightarrow {}^2H + e^+ + \nu_e$
- Man-Made : ~few MeV
  - Nuclear reactors - byproduct
- Man-Made : ~ 0.5 MeV - 1 GeV (10^9 eV)
  - Accelerators - DAR, DIF
- Atmospheric : ~1 - 10 GeV
  - cosmic rays = proton from outer space + atm = showers, creates atmospheric neutrinos

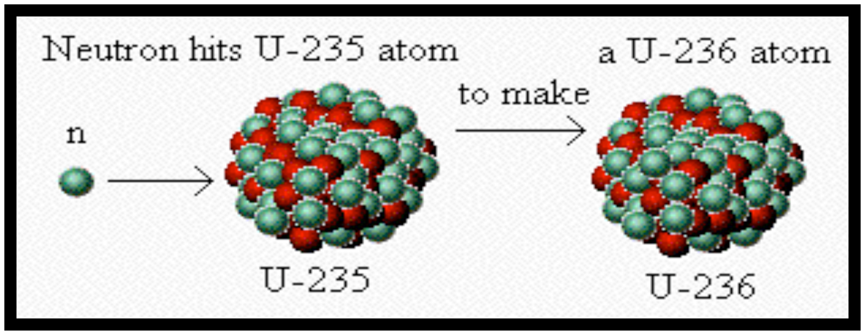
Solar Neutrinos

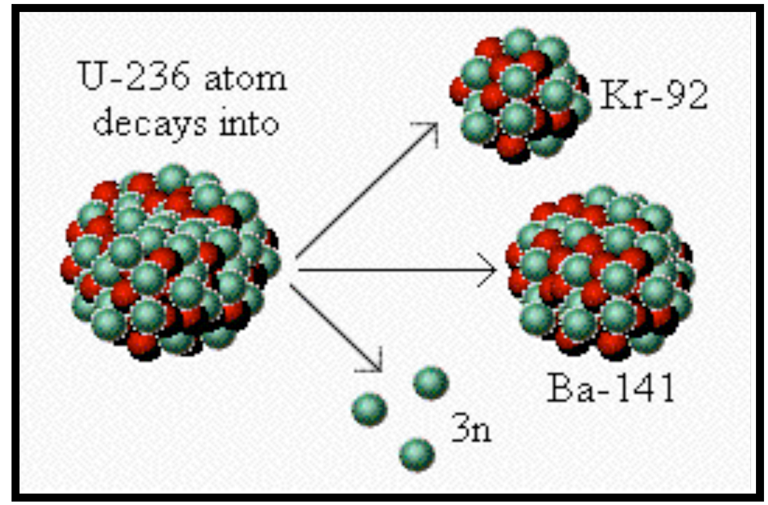


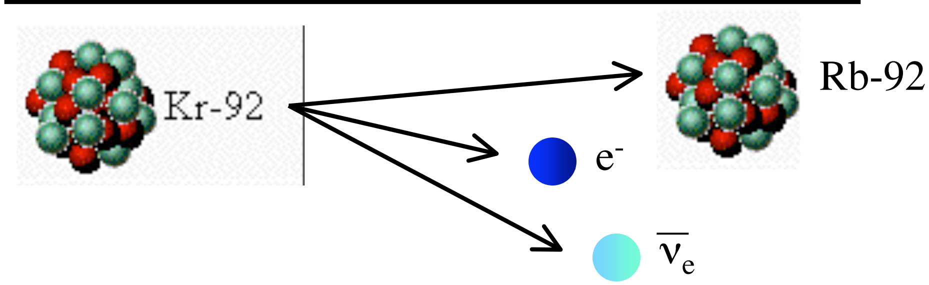
pp	$\rightarrow$	$^2H + e^+ + \nu_e$	ppI
$^2H + p$	$\rightarrow$	$^3He + \gamma$	
$^3He + {}^3He$	$\rightarrow$	$^4He + 2p$	
$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$	ppII
$e^- + {}^7Be$	$\rightarrow$	$^7Li + \nu_e$	
$^7Li + p$	$\rightarrow$	$2\,^4He$	
$p + {}^7Be$	$\rightarrow$	$^8B + \gamma$	ppIII
^8B	$\rightarrow$	$^8Be^* + e^+ + \nu_e$	
$^8Be^*$	$\rightarrow$	$2\,^4He$	

Theoretical uncertainties

Nuclear Reactor Neutrinos

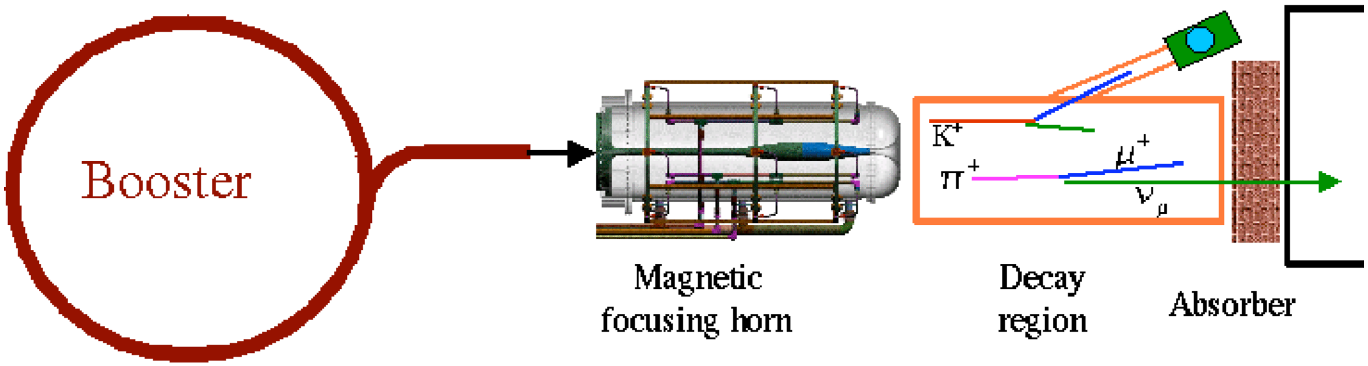






- Reactors = only source of a pure anti-neutrino beam, pure electron-flavor beam!
- Anti-neutrinos are emitted by the radioactive fissile products when they disintegrate via beta decay
- ~few MeV Energy

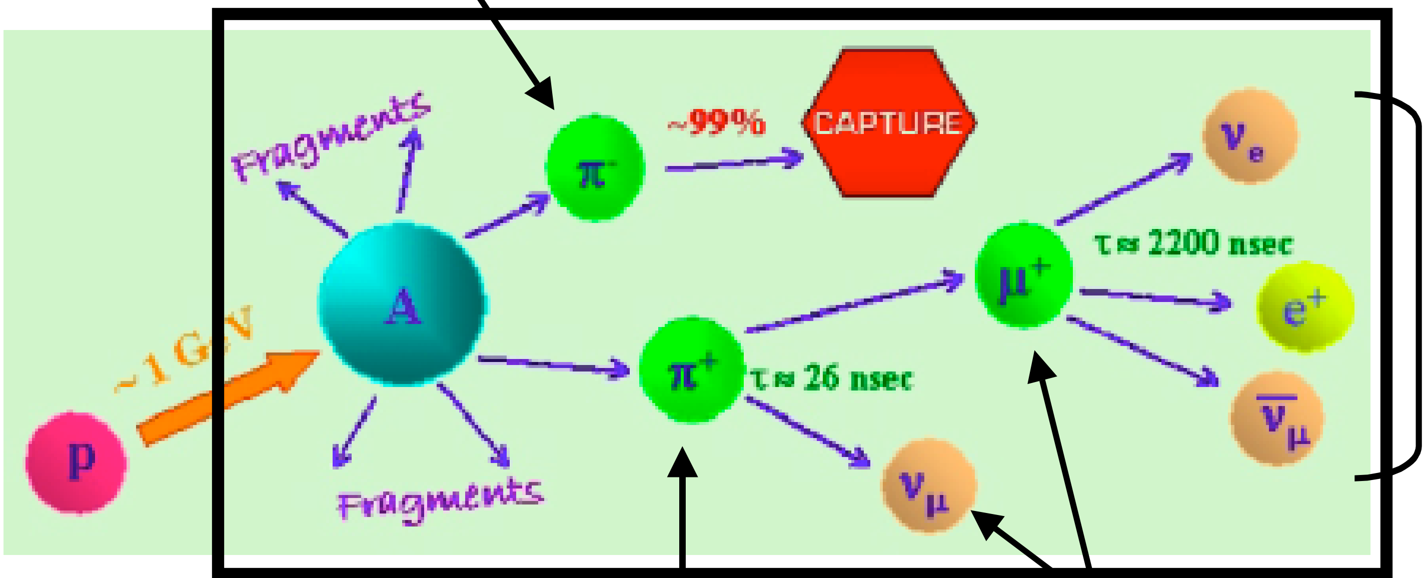
Accelerator-Based Neutrinos



- Beam of protons + a target material = mesons (π, K)
- Mesons decay into the neutrino beam seen by a detector
  - $K^+ / \pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$
  - $K^o_L \rightarrow \pi^+ + \mu^- + \overline{\nu}_\mu$
  - Create neutrinos via meson Decay at Rest, Decay in Flight

Decay At Rest

π^- absorbed by target



E range up to 52.6 MeV

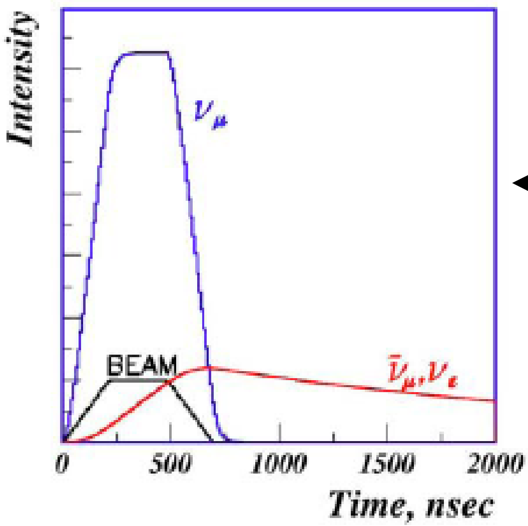
Target Area

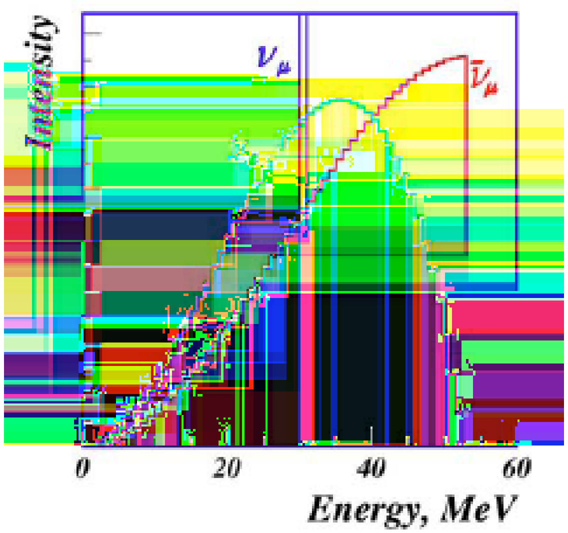
π^+DAR

Mono-Energetic!
ν_μ= 30 MeV

Hg+ target, SNS (Spallation Neutron Source, Oak Ridge)

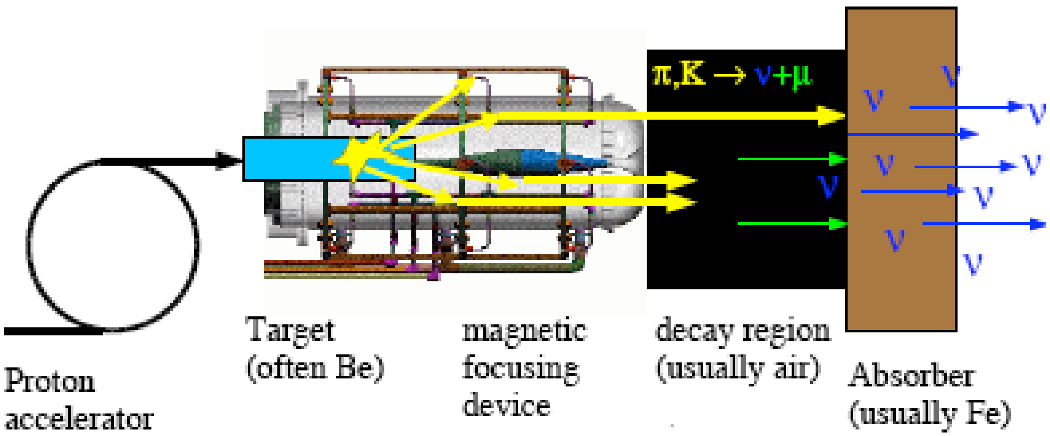
Decay At Rest

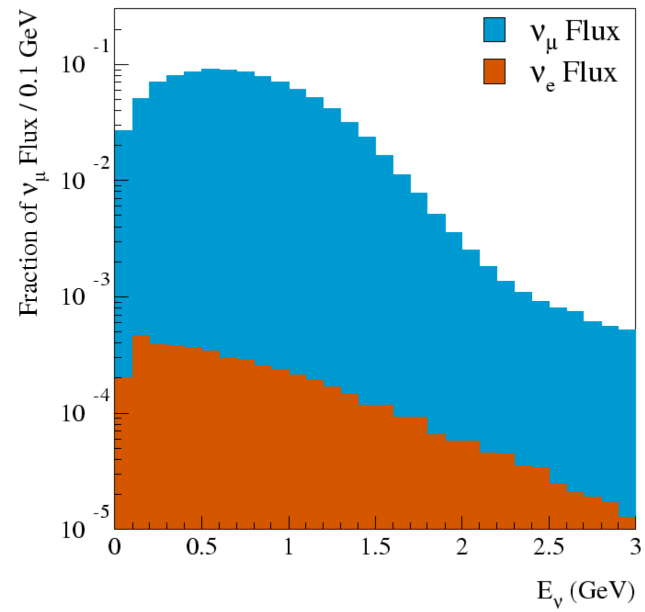




- Advantage = Know timing of beam, lifetime of particles, use to greatly suppress cosmic ray background
- Advantage = extremely well defined flux
- Disadvantage = Low E limits choices of neutrino interaction signal
- Disadvantage = Beam is isotropic - no directionality
  - Hard to make an intense isotropic beam

Decay In Flight

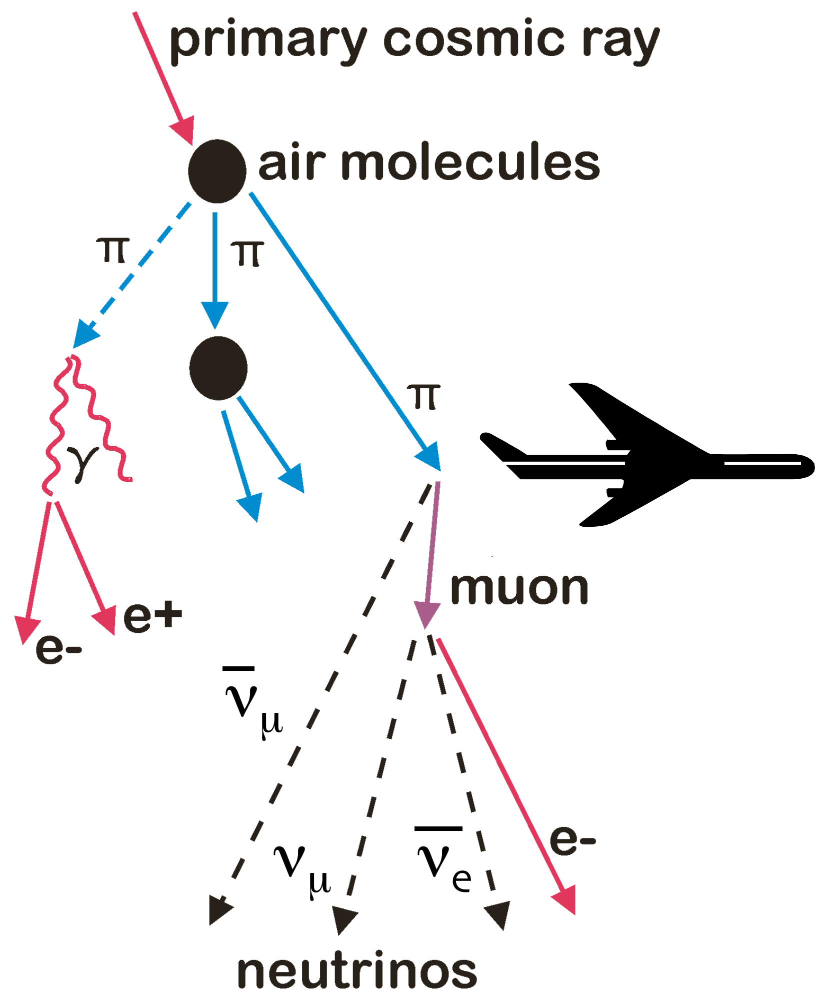




- Advantage : more intense beam because mesons are focused (not isotropic)
- Advantage : can select neutrino, anti-nu beam
- Disadvantage : difficult to understand the flux (in content and in E)!

Atmospheric Neutrinos

- High energy protons + nuclei collide in the upper atmosphere = high energy pions
- Pions → muons + neutrinos
- Muons → neutrinos
- $(\nu_\mu + \overline{\nu}_\mu) : (\nu_e + \overline{\nu}_e) = 2 : 1$



Detecting Neutrinos

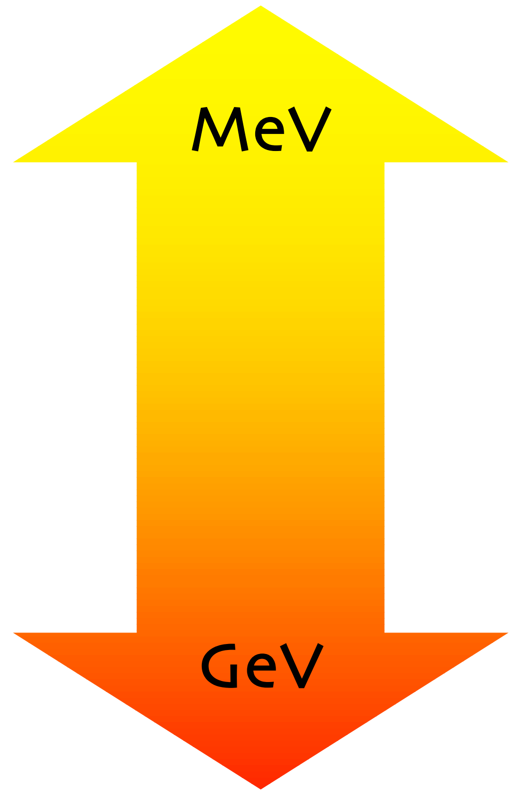
Interactions with Matter

Detecting Neutrinos

- Neutrinos interact with material in the detector. It's the outcome of these interactions that we look for
- **Neutrinos can interact with :**
  - Electron in the atomic orbit
  - The nucleus as a whole
  - Free proton or nucleon bound in nucleus
  - A quark

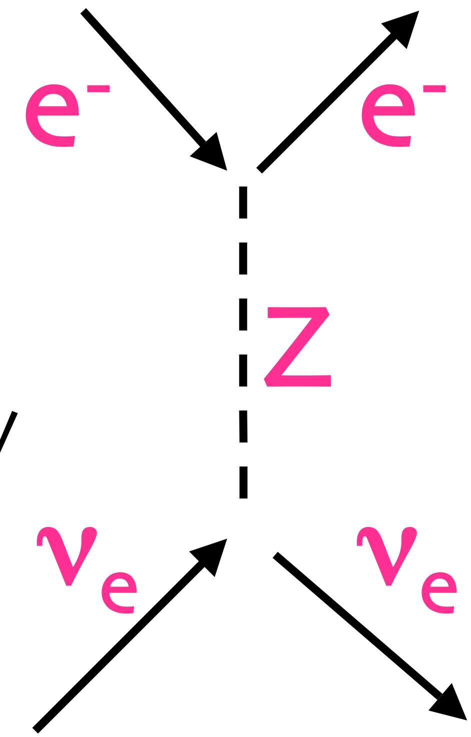
Neutrino Interactions

- Elastic Scattering
- Quasi-Elastic Scattering
- Single Pion Production
- Deep Inelastic Scattering



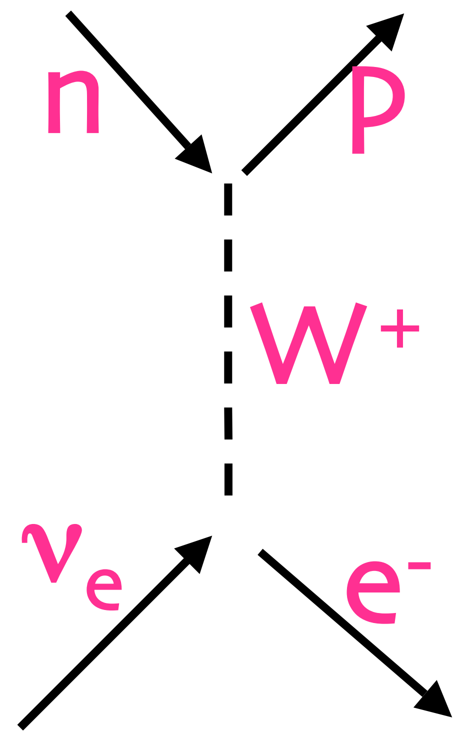
Elastic Scattering

- Target left intact
- Neutrinos can elastic scatter from any particle (electrons, protons)
- Neutrino imparts recoil energy to target = how we observe these interactions



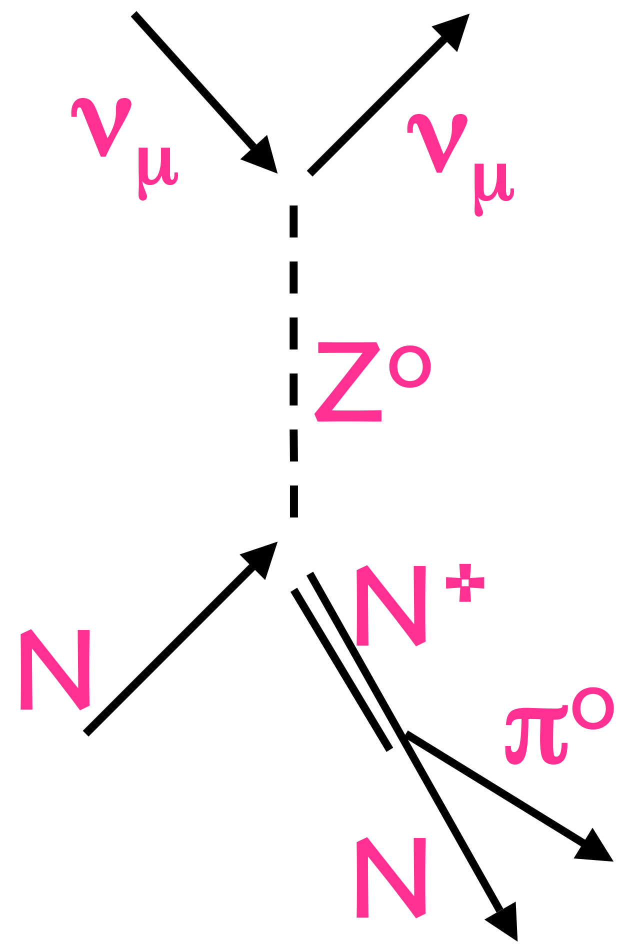
Quasi-elastic Scattering

- Neutrino in, charged lepton out
- Target changes type
- Need to conserve electric charge at every vertex
- Need minimum neutrino E
  - Need enough CM energy to make the two outgoing particles



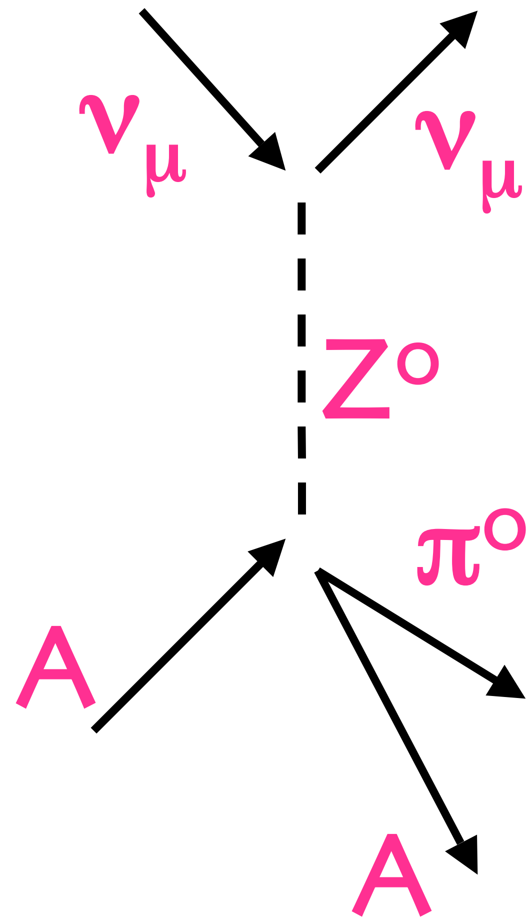
Single Pion Production

- Resonant
  - neutrino scattering from a nucleon
  - Nucleon resonance is excited, decays back into it's ground state nucleon
  - Emits one or more mesons in the de-excitation process



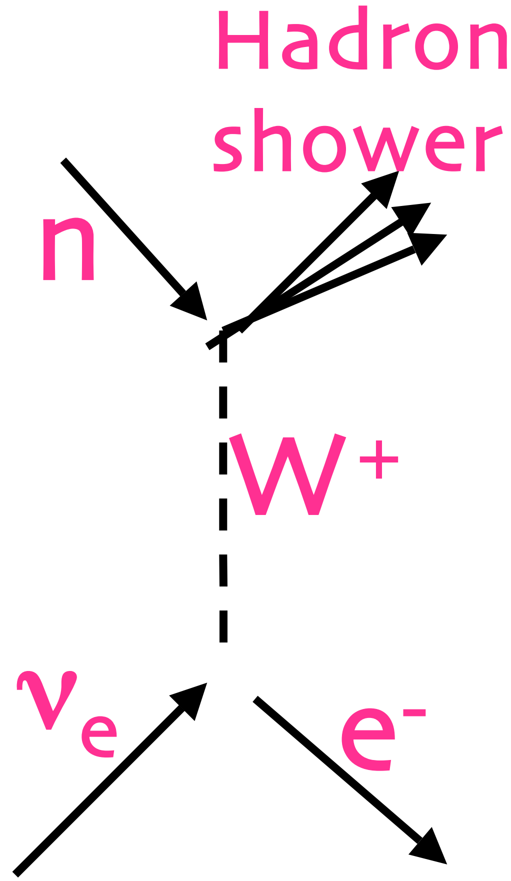
Single Pion Production

- Coherent
  - neutrino scatters from entire nucleus
  - nucleus does not break up / no recoil nucleon
  - Requires low momentum transfer (to keep nucleus intact)
  - No transfer of charge, quantum numbers



Deep Inelastic Scattering

- Scattering with very large momentum transfers
- Incoming neutrino produces a W boson, turns into partner lepton
- W interacts with quark in nucleon and blows it to bits (ie inelastic)
- Quarks shower into a variety of hadrons, dissipating the E carried by the W boson (ie deep)



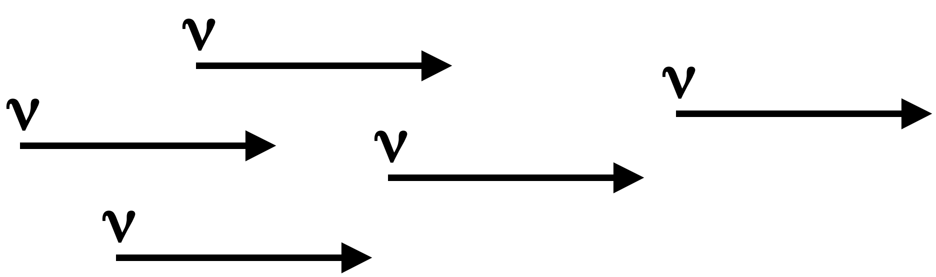
How often do these interactions occur?

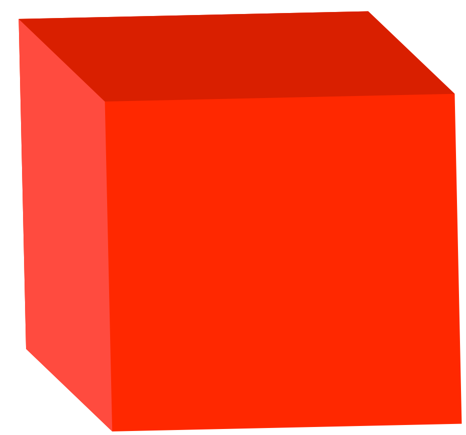
Cross Sections

- Cross section = probability that an interaction will take place

Volume of detector = V (m^3)
Density of nucleons = n ($1/m^3$)

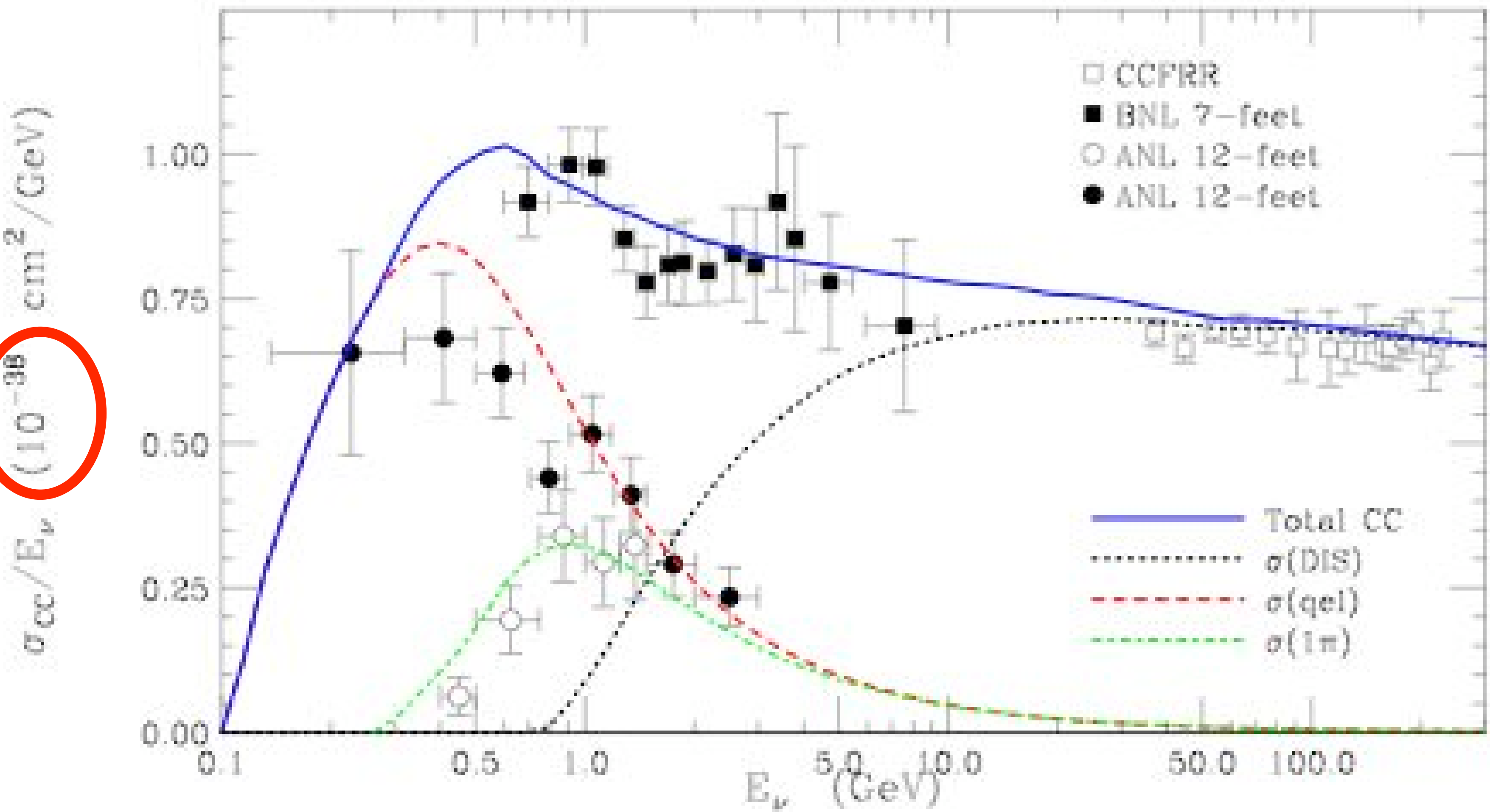
Neutrino flux = ϕ ($1/m^2 s$)





$$\boxed{\text{Cross Section } \sigma \ (m^2) = \frac{\#\ \text{neutrino interactions per second}}{\text{Flux} * \underbrace{\text{Density} * \text{Volume}}_{\#\ \text{of targets}}}}$$

Neutrino Cross Sections



Detecting Neutrinos

Detection Techniques

Observing Neutrino Interactions

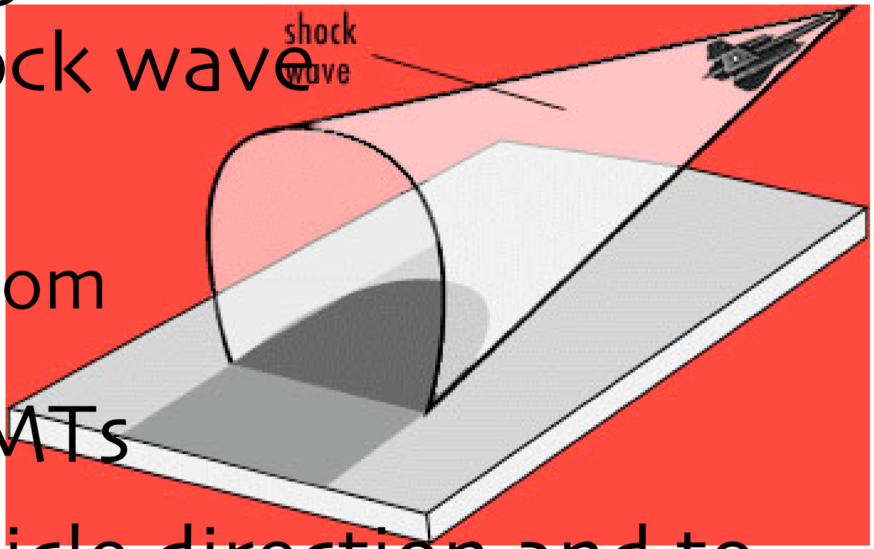
- Very small cross sections for interactions!
- Need large-scale detectors
- Radiochemical reactions
  - $\nu_e + {}^{37}Cl = {}^{37}Ar + e^-$
  - Measure neutrino flux by counting number of produced Ar atoms
  - No time, direction information
- Passage of charged particles through matter leaves a distinct mark
  - Cerenkov effect / light
  - Scintillation light
  - Provides time, direction information

Find νs

Find products of ν ints

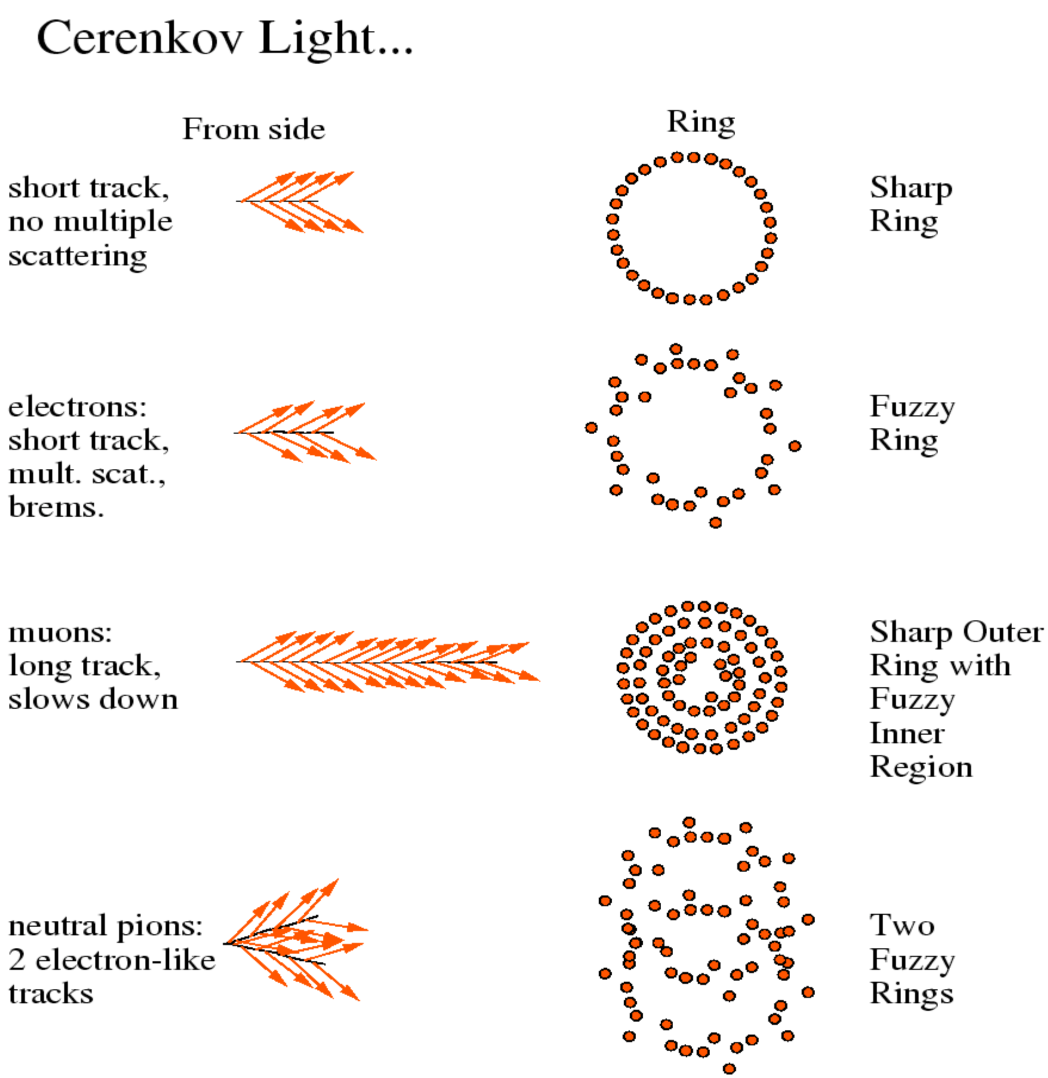
Cerenkov Light

- Charged particles with a velocity greater than the speed of light * in the medium* produce an E-M shock wave
  - $v > 1/n$
  - Similar to a sonic boom



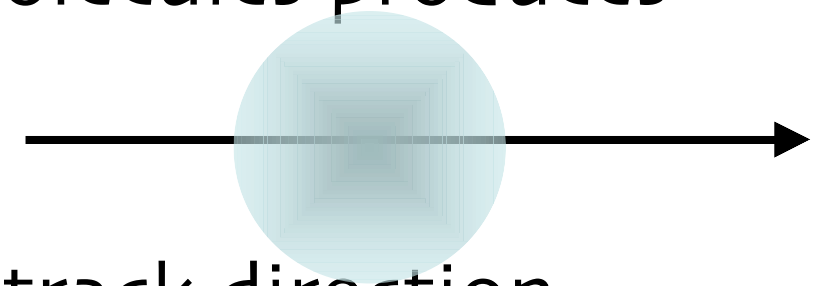
- Light detected by PMTs
- Use to measure particle direction and to reconstruct interaction vertex
- Prompt light signature

Cerenkov Light



Scintillation Light

- Charged particles moving through a material deposit energy in the medium, which excites the surrounding molecules
- The de-excitation of molecules produces scintillation light
- Isotropic, delayed
- No information about track direction
- Can use PMT timing information to locate interaction point

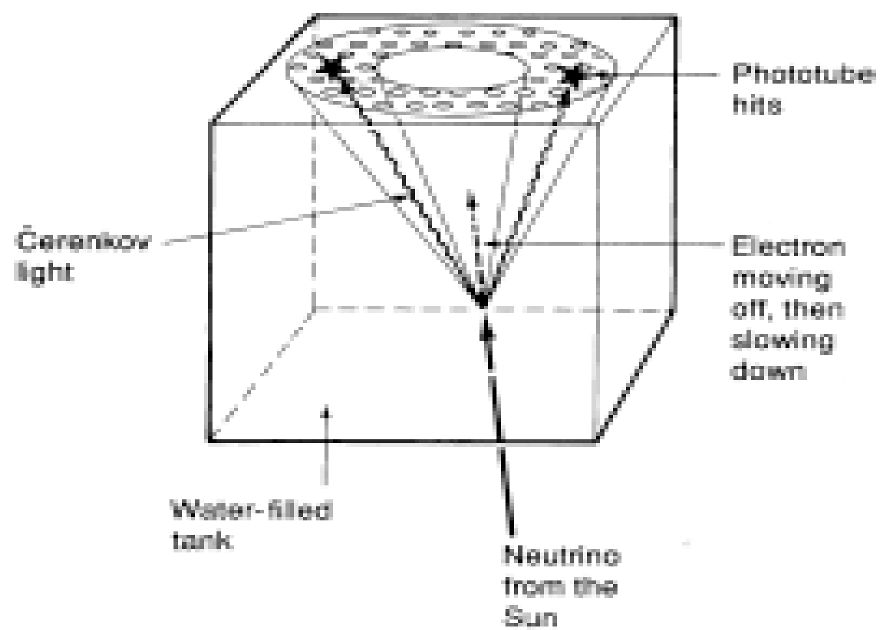


Detecting Neutrinos

Examples of Detectors

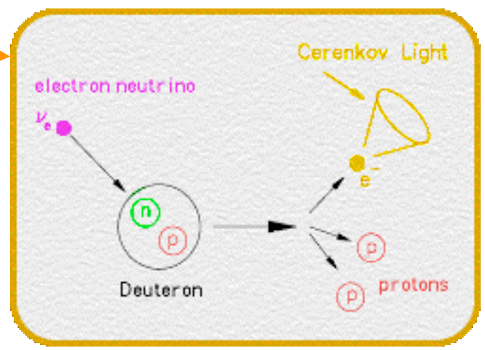
Neutrino Detectors : Solar (Atm, Accel)

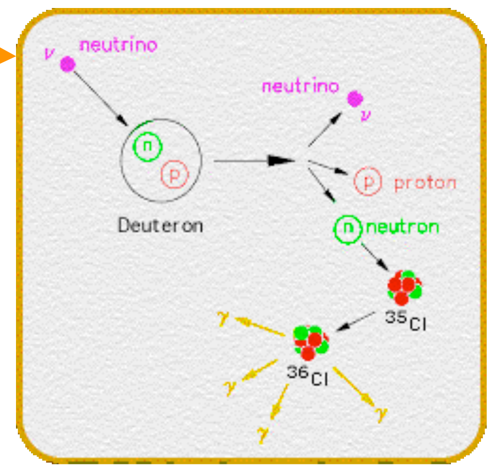
- [1] Detect Cerenkov light from ν interacting with water in Kamiokande
  - Electron neutrino scatters elastically from an atomic electron
  - Scattered ele follow the direction of the incoming ν (~15 deg. max deviation)
  - Threshold E for interaction = 4 to 5 MeV



Neutrino Detectors : Solar

- [1] Detect Cerenkov light from ν interacting with *heavy* water : SNO
  - Deuterium nuclei in water = distinguish electron neutrinos from other types
  - Neutrino interaction rates are higher in heavy water than ordinary water = uses less water, less collection time to have same statistics as Kamiokande
  - NC : $D + \nu = p + n + \nu$
  - CC : $D + \nu_e = p + p + e$



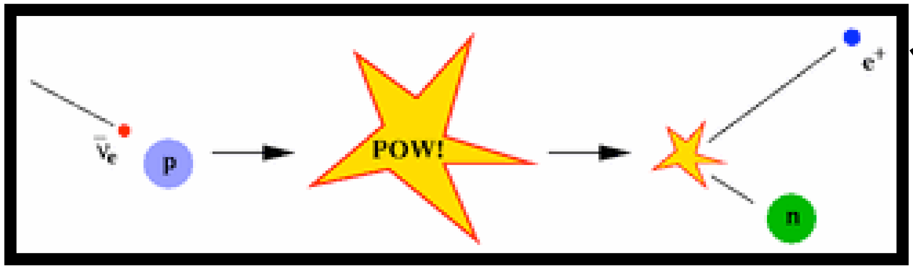


Neutrino Detectors : Solar

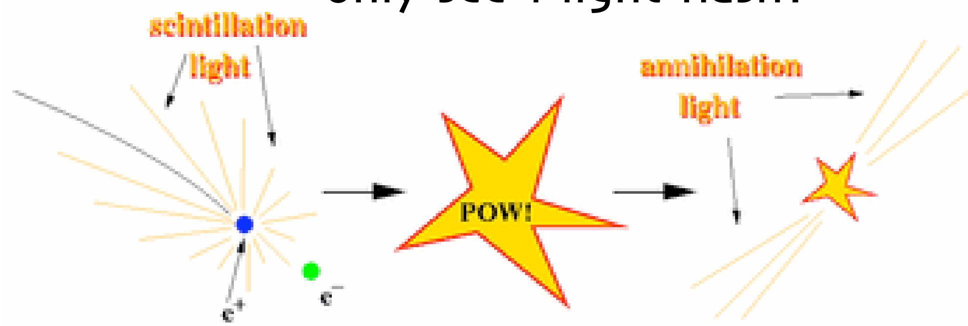
- [2] Detect transformation of atoms under neutrino interaction
  - $\nu_e + {}^{37}Cl = {}^{37}Ar + e^-$: Homestake
    - Only sensitive to ν from ^{7}Be, ^{8}B branches (>0.8 MeV)
  - $\nu_e + {}^{71}Ga = {}^{71}Ge + e^-$: Gallex
    - Sensitive to ν from initial proton fusion reaction (>233 keV)

Neutrino Detectors : Reactor

Kamland scintillator detector

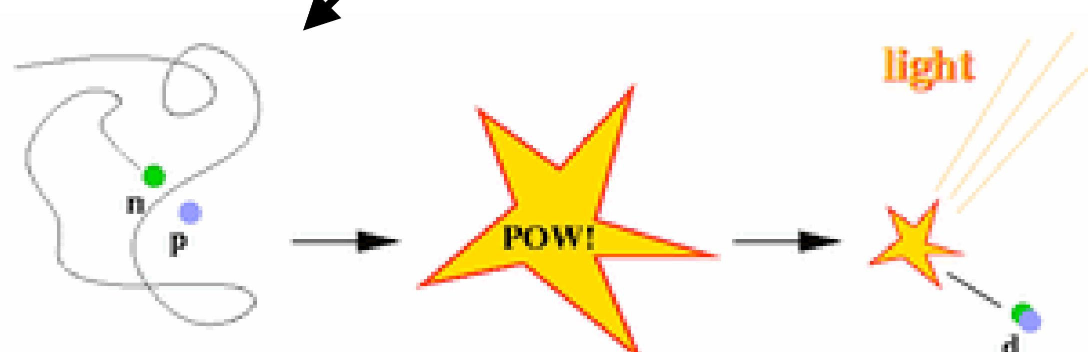


happens so quickly you
only see 1 light flash!

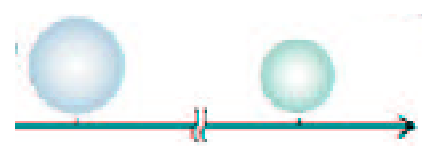


neutron
thermalization
mean time = 200 μs

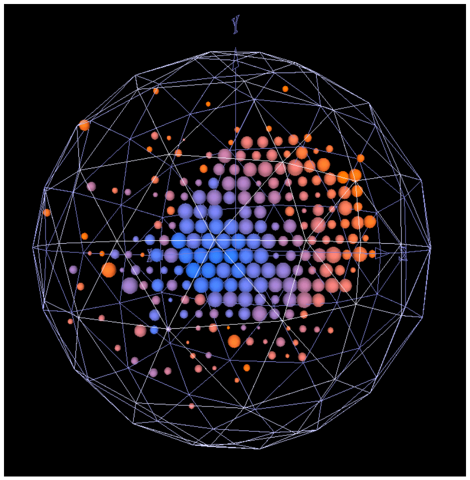
two 0.511 MeV photons



one 2.2 MeV photon

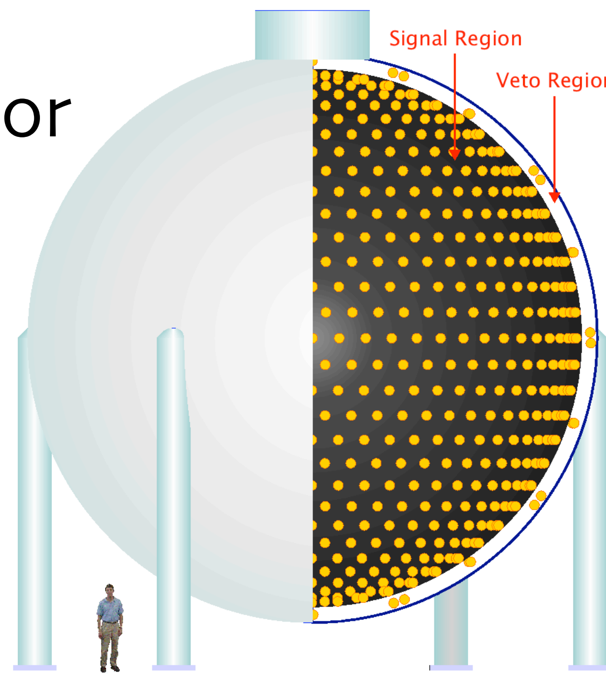


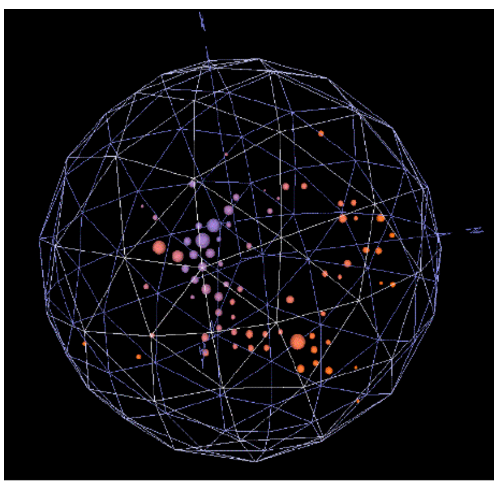
Neutrino Detectors : Accelerator

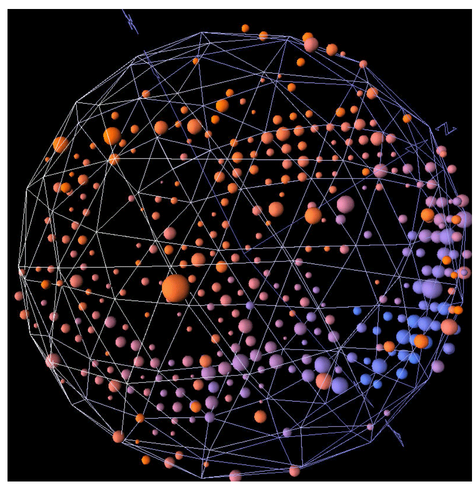


Mainly a
Cerenkov detector

MiniBooNE Detector



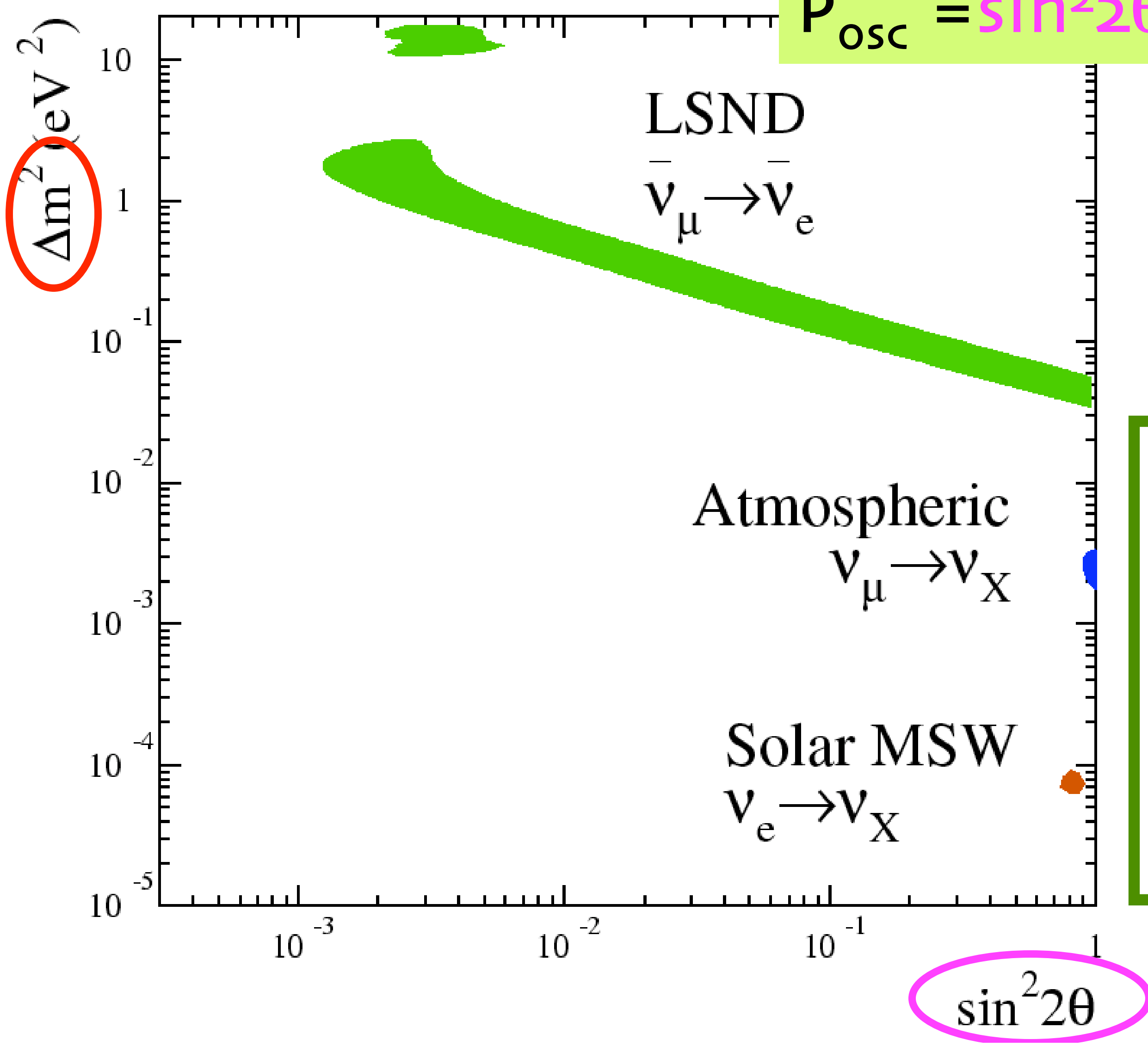




Oscillation Results

Oscillation Results

$$P_{osc} = \sin^2 2\theta \ \sin^2\left(\frac{1.27\ \Delta m^2\ L}{E}\right)$$



$$\Delta m^2 = m_a^2 - m_b^2$$

If there are only 3 :

$$\Delta m_{ac}^2 = \Delta m_{ab}^2 + \Delta m_{bc}^2$$

Sampling Neutrino Theories

AKA : explaining the three oscillation results

Other Theories

- Sterile Neutrinos
  - RH neutrinos that don't interact (Weak == LH only)
- CPT Violation
  - 3 neutrino model, $\Delta m_{anti-\nu}^2 > \Delta m_{\nu}^2$
  - Run in neutrino, anti-neutrino mode, compare measured oscillation probability
- Mass Varying Neutrinos
  - Mass of neutrinos depends on medium through which it travels
- Lorentz Violation
  - Oscillations depend on direction of propagation
  - Oscillations explained by small Lorentz violation
  - Don't need to introduce neutrino mass for oscillations!
  - Look for sidereal variations in oscillation probability

Things I Haven't Covered

- How neutrinos can get mass
  - Dirac vs Majorana type particles

Finally : Open Questions

- What is the mass of each neutrino?
- Do neutrinos have a magnetic moment?
  - Expect a non-zero moment if massive
- How do they get their mass?
  - ie, are the neutrino and anti-neutrino the same or different?
- Is the LSND oscillation signal correct?

Standard Model of Physics

Up 3 MeV 1/312 H atom	Charm 1500 MeV 1.5 H atom	Top 175000 MeV 1 Au atom
Down 6 MeV 1/156 H atom	Strange 170 MeV 1/5 H atom	Bottom 4500 MeV 1 He + 1 H atom
Electron 0.511 MeV 1/2000 H atom	Muon 105 MeV 1/9 H atom	Tau 1782 MeV 2 H atoms
Electron ν 0 MeV	Muon ν 0 MeV	Tau ν 0 MeV